3D FEM SIMULATIONS OF THE ROLLING OF STATOR VANES, INCLUDING TOOL DEFORMATION

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Summary

Tool deformation is an important issue in the shape rolling of stator vanes as it directly influences the thickness of the rolled vane. This means that for the design of an accurate production process the deformation of the tools has to be accounted for. The shape rolling of symmetrical straight vanes has been investigated. Because these vanes have a constant cross-section over the length, this rolling process can be considered as a stationary process. Therefore an ALE formulation is suitable to calculate the steady state. The deformation of the sheet as well as the deformation of the tools have been calculated with the developed finite element model. Some results of these simulations are presented in this paper.

Keywords: shape rolling, tool deformation, ALE

1 Introduction

Stator vanes for gas-turbines or aero engines can be manufactured with a cold shape rolling process, which will be explained in more detail in Section 2. During this rolling process, the thickness of a strip of sheet material is reduced in order to obtain the right thickness at the right position at the right cross-section of the vane. However, sometimes thickness deviations are found after the first trial runs. An important reason for these deviations is the deformation of the rolling tools. Unfortunately sometimes a number of process redesign cycles are necessary, in which the tools or process parameters are adapted, in order to produce vanes within the required tight tolerances.

The objective of this research is to improve the design of the rolling tools for new types of vanes. This requires a thorough knowledge of the rolling of vanes. Therefore this process has been modelled with FEM, which should lead to additional insights.

2 The shape rolling process

The tools used for the shape rolling process are drawn in **Figure 1**. Only one of the tools, the roll-die, rotates, which differs from the usual shape rolling process. The other tool, the die-plate is fixed to the frame of the machine. Both tools contain the profile of the vane.

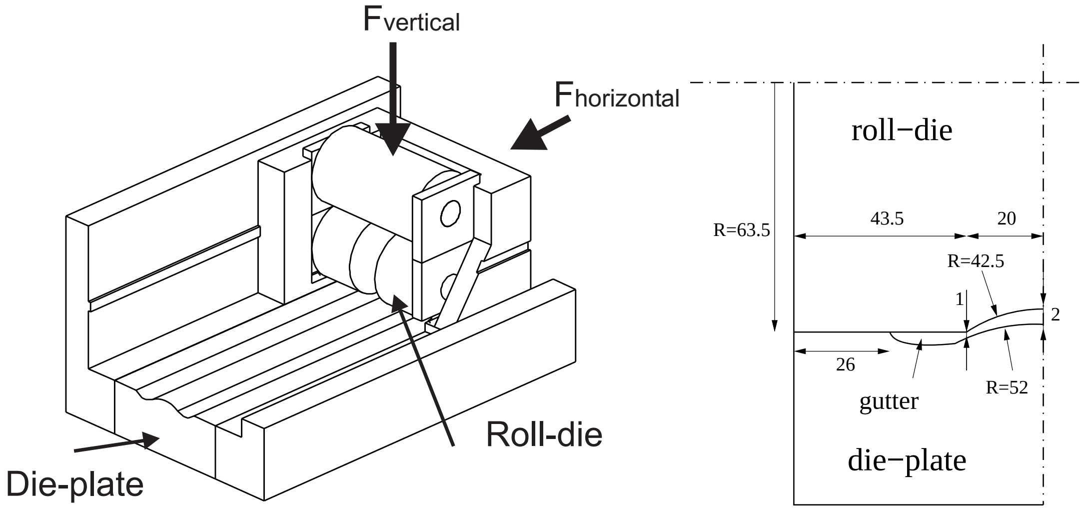

Figure 1: *Tools of the rolling process with dimensions [mm].*

Due to the applied horizontal force and a cog-wheel construction, the roll-die rolls over the die-plate. This deforms the strip, which is clamped to the die-plate on one end, into a vane. The length of the final product is limited to the perimeter of the roll-die. The vertical force, applied through a support roll, controls the vertical movement of the roll-die. Normally, the roll-die makes contact with the die-plate during rolling. However, when the applied vertical force is too low the roll-die will be lifted.

The vane, which is investigated in this paper, is produced by the tools of **Figure 1**. The shape of this symmetrical straight vane is similar to the shape of a real vane. The vane is 2 mm thick in the middle and 1 mm thick at the leading and trailing edges. Besides elongation, lateral spread is made possible with a gutter next to the vane profile. Some experimental data are available for this product to validate the simulations [1].

3 FEM model

When the start and the end of the process are neglected, the rolling of straight vanes can be considered as a stationary process. In relation to a domain that moves with the axis of the roll-die, the roll-die only rotates and the die-plate moves opposite to the rolling direction. An appropriate FEM formulation for the calculation of the steady state of a stationary process is the Arbitrary Lagrangian Eulerian (ALE) method. In this formulation are the grid displacements independent of the material displacements. Therefore it is possible to model the shape rolling process as a flow problem, while following free surfaces, keeping elements at regions with large deformations and preserving a sufficient element quality. The used finite element code DiekA, developed at the University of Twente, contains such an ALE formulation.

Special contact elements are used to describe the contact between the strip and the tools. These elements are based on a penalty formulation [2]. Therefore some penetration of the tools and vane into each other will exist. This penetration should be much lower than the tool deformations, but this requires high penalties which deteriorate the convergence behavior of the simulation. So a compromise has to be made.

The nodes of the contact elements have to be connected to the two contacting bodies. A pair of contact nodes should be kept opposite to each other during the entire simulation in order to calculate a correct penetration distance. It is shown for a 2D rolling application, that this is possible for stationary processes, using the ALE method [2]. However this complicates the creation of the initial mesh of the tools and the vane, as the contacting surfaces should have a similar mesh.

We start by meshing an estimate of the expected steady state geometry of the strip/vane. Having this mesh the tools can be meshed, such that the contact elements can be defined correctly. Due to symmetry only one half of the strip and tools has to be modelled. The initial mesh is shown in **Figure 2**. Respectively 7748, 3640, 6006 and 1408 elements are used for the die-plate, strip, roll-die and contact.

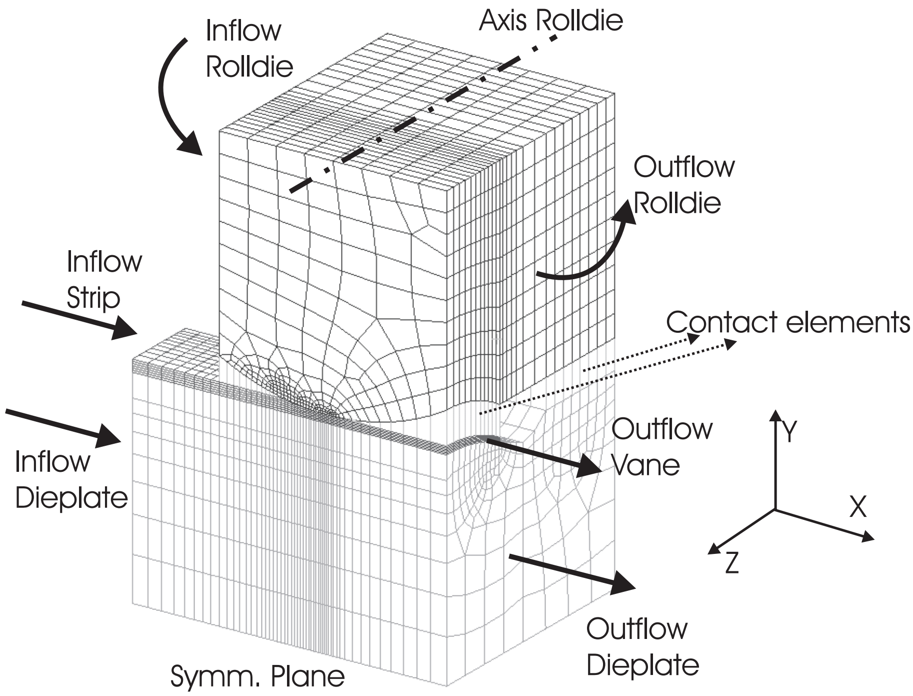

Figure 2: *Initial mesh.*

A rotation is prescribed to the nodes on the horizontal plane through the axis of the roll-die. Because the vane is clamped to the dieplate, the same material displacement is prescribed to the outflow boundaries of the vane and the dieplate. The vertical force is applied to the bottom face of the die-plate, which was the easiest solution. So the die-plate is allowed to move up and down instead of the roll-die, but the mutual displacement is not influenced. The grid displacement of all nodes is taken equal to zero in x-direction.

Therefore the material ”flows” through the mesh in rolling direction, which results in in- and outflow boundaries. The y- and z- grid displacement of the nodes on the free and contact surfaces is calculated in such a way that they remain on these surfaces. Hereby the element sizes can be controlled in a way that the smallest elements are kept at the locations with the largest reduction [3]. Internal nodes are repositioned in order to preserve a sufficient element quality. The simulation is continued until a steady state is reached, i.e. the mesh and state variables do not change anymore.

Simulations with the ALE formulation take some extra work, which introduces some numerical errors. First the state variables have to be transferred from the old to the new mesh. This transfer is performed with a convection scheme, which is diffusive in flow direction, but shows very little cross-wind diffusion [3]. Next the grid displacement has to be defined. Material can be added or removed during the relocation of the nodes on the free surfaces; Repeatedly an error in the same direction causes small errors to grow. These errors will also propagate in downstream direction. When the current mesh is used, the radius of the roll-die ”grows” about 0.02 mm due to these errors. Mesh refinement will decrease this error.

The vane is rolled from aluminium sheet in soft temper. The sheet is modelled with an elasto-plastic material model with a VonMises flow rule. The hardening is described by a Nadai stress-strain curve (**Table 1**). The dies are made from a cold work tool steel, which remains elastic during the rolling of the relatively soft aluminium. But in case of harder sheet materials, as stainless steel, the yield stress of the tools might be exceeded.

Table 1: *Material properties*

	AA 6061-O	tool steel
E-modulus [GPa]	70	217
ν	0.33	0.28
$\sigma_y(0)$ [MPa]	83	~ 2000
$\sigma_y(\varepsilon^p)$ [MPa]	$1+170(0.0261+\varepsilon^p)^{0.2}$	—

4 Results

Some characteristic results of the simulations of the rolling of the investigated vane are shown here and compared with the available experimental results. The dimensions of the undeformed strip are kept constant: 40mm wide and 3mm thick, but these values can be varied to influence the process. Simulations have been performed with a range of different vertical forces keeping the friction coefficient constant ($\mu = 0.11$).

In **Figure 3**, the calculated contours of the vanes and the deviation from the nominal thickness are plotted for an increasing vertical force. The nominal thickness is the gap between the tools in the unloaded situation. It can be seen that the thickness of the vane decreases and the spread increases with increasing vertical force. For the lowest force of 75kN the roll-die is lifted from the die-plate, therefore the vane becomes much too thick. Increasing the force to 150kN establishes the contact between the tools at the sides. Now the thickness of the vane comes close to the intended value. A further increase of the vertical force gives a larger deviation. The effect of an increasing force is now mainly determined by the stiffness of the contact between the die-plate and roll-die.

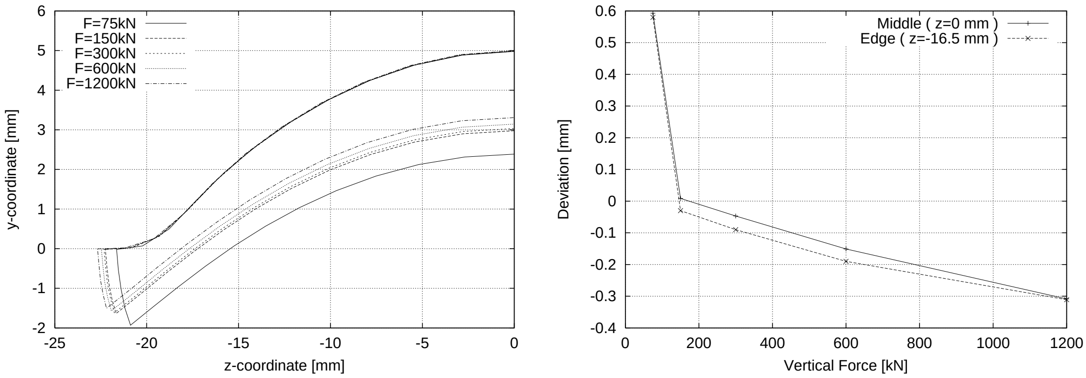

Figure 3: *Contour and thickness deviation of the vane.*

From **Figure 3** can be concluded that an increasing force affects the thickness of the vane as much in the middle as close the edge (16.5 mm from the middle). However the deviation at $z = -16.5$ is larger than the deviation in the middle. The largest deviation coincides with the maximum of the hydrostatic pressure. Therefore changing the vertical force only will not result in a correct thickness over the entire width of the vane.

Increasing the friction coefficient leads to higher hydrostatic pressures. Therefore higher vertical forces will be needed to close the tools. For $F = 150kN$ an increase of the friction coefficient form $\mu = 0.11$ to 0.2 results in open tools and too thick vanes. Furthermore the position of the neutral lines of the shear stresses in the contact [4] changes with a varying friction coefficient, which influences the material flow (spread). These results show that the vane thickness is less sensitive for changing process conditions at high vertical forces than at lower forces.

In order to get some information about the elongation and spread of the strip due to the rolling process an equidistant grid has been scratched onto the undeformed strip. The deformation of this grid is measured after rolling. An examination of the deformed grids proved that the assumption of a stationary process is valid for straight vanes, except for the start and end of the process.

In **Figure 4** the ratio of the distance between two gridlines in rolling direction in the deformed and undeformed state is given. It can be seen that this ratio is below one in the middle of the vane (compression) and increases towards the edges (elongation). The same information can be extracted from the simulation by tracking material points with an equal initial z-coordinate. **Figure 4** shows a vertical cross-section through the axis of the roll-die with the initial (=undeformed) z-coordinate of the vane and the tools. Considering that the deformations of the tools are very small compared to the deformation of the vane, it can be concluded that the results of the simulation agree with the experimental results.

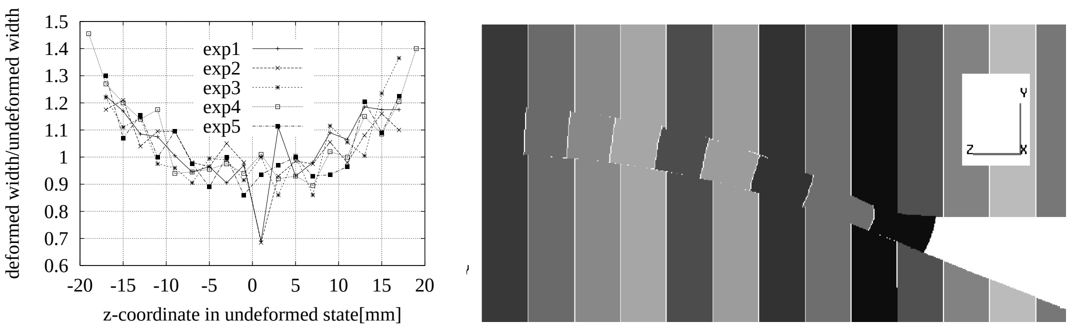

Figure 4: *Comparison of experiments (left) and simulation $F = 300kN$ (right).*

5 Conclusions

The rolling of straight stator vanes has been simulated, taking into account the deformation of the tools. The nodes can be relocated such that pairs of contact nodes remain opposite to each other with the ALE method. Therefore this method is a suitable formulation for stationary processes. Although further experiments are needed to validate the results of the simulations for varying vertical forces, the current model already increases the insight in this process. The model described here can also be used to simulate the rolling of real straight vanes (i.e. non-symmetrical vanes).

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